

# Sensitivity of T2KK to non-standard interactions

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Assuming only the non-zero electron and tau neutrino components  $\epsilon_{ee}$ ,  $\epsilon_{e\tau}$ ,  $\epsilon_{\tau\tau}$  of the non-standard matter effect and postulating the atmospheric neutrino constraint  $\epsilon_{\tau\tau} = |\epsilon_{e\tau}|^2/(1 + \epsilon_{ee})$ , the sensitivity to the non-standard interaction in neutrino propagation of the T2KK neutrino long-baseline experiment is estimated. It is found that T2KK can constrain the parameters  $|\epsilon_{ee}| \lesssim 1$ ,  $|\epsilon_{e\tau}| \lesssim 0.2$ .

It is expected that the undetermined oscillation parameters such as  $\theta_{13}$  and  $\delta$  are expected to be measured in future neutrino long-baseline experiments (see, e.g., Ref. [1]). As in the case of B factories, such highly precise measurements will enable us to search for deviation from the standard three-flavor oscillations. One such possibility is the effective non-standard neutral current-neutrino interaction (NSI) with matter

$$\mathcal{L}_{\text{eff}}^{\text{NSI}} = -2\sqrt{2}\epsilon_{\alpha\beta}^{fP}G_F(\bar{\nu}_\alpha\gamma_\mu P_L\nu_\beta)(\bar{f}\gamma^\mu P f'), \quad (1)$$

where  $f$  and  $f'$  stand for fermions (the only relevant ones are electrons, u, and d quarks),  $G_F$  is the Fermi coupling constant, and  $P$  stands for a projection operator that is either  $P_L \equiv (1 - \gamma_5)/2$  or  $P_R \equiv (1 + \gamma_5)/2$ . In the presence of the interaction Eq. (1), the standard matter effect is modified. Using the notation  $\epsilon_{\alpha\beta} \equiv \sum_P (\epsilon_{\alpha\beta}^{eP} + 3\epsilon_{\alpha\beta}^{uP} + 3\epsilon_{\alpha\beta}^{dP})$ , the hermitian  $3 \times 3$  matrix of the matter potential becomes

$$\mathcal{A} \equiv A \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{\mu e} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{\tau e} & \epsilon_{\tau\mu} & \epsilon_{\tau\tau} \end{pmatrix}, \quad (2)$$

where  $A \equiv \sqrt{2}G_F N_e$ .

Constraints on  $\epsilon_{\alpha\beta}$  from various neutrino experiments have been discussed by many people (see, e.g., Ref. [2] and references therein). Since  $\epsilon_{\alpha\beta}$  in Eq. (2) are given by  $\epsilon_{\alpha\beta} \sim \sum_P (\epsilon_{\alpha\beta}^e + 3\epsilon_{\alpha\beta}^u + 3\epsilon_{\alpha\beta}^d)$  in the case of experiments on the Earth, we have the following constraints [2] at 90% CL:

$$|\epsilon_{ee}| < 4 \times 10^0, \quad |\epsilon_{e\mu}| < 3 \times 10^{-1},$$

$$\begin{aligned} |\epsilon_{e\tau}| &< 3 \times 10^0, \quad |\epsilon_{\mu\mu}| < 7 \times 10^{-2}, \\ |\epsilon_{\mu\tau}| &< 3 \times 10^{-1}, \quad |\epsilon_{\tau\tau}| < 2 \times 10^1. \end{aligned} \quad (3)$$

On the other hand, it was shown in Ref. [3] that

$$|\epsilon_{e\tau}|^2 \simeq \epsilon_{\tau\tau}(1 + \epsilon_{ee}) \quad (4)$$

should be satisfied to be consistent with the high-energy atmospheric neutrino data. In the standard three-flavor scheme, the high-energy behavior of the disappearance oscillation probability is

$$\begin{aligned} &1 - P(\nu_\mu \rightarrow \nu_\mu) \\ &\simeq \left(\frac{\Delta m_{31}^2}{2AE}\right)^2 \left[ \sin^2 2\theta_{23} \left(\frac{c_{13}^2 AL}{2}\right)^2 \right. \\ &\quad \left. + s_{23}^2 \sin^2 2\theta_{13} \sin^2 \left(\frac{AL}{2}\right) \right]. \end{aligned} \quad (5)$$

In fact it was pointed out [4] that the generic matter potential (2) leads to the high-energy behavior of the disappearance oscillation probability

$$1 - P(\nu_\mu \rightarrow \nu_\mu) \simeq c_0 + \frac{c_1}{E} + \mathcal{O}\left(\frac{1}{E^2}\right), \quad (6)$$

where  $c_0$  and  $c_1$  are functions of  $\epsilon_{\alpha\beta}$ , and that  $|c_0| \ll 1$  and  $|c_1| \ll 1$  implies  $|\epsilon_{e\mu}|^2 + |\epsilon_{\mu\mu}|^2 + |\epsilon_{\mu\tau}|^2 \ll 1$  and  $||\epsilon_{e\tau}|^2 - \epsilon_{\tau\tau}(1 + \epsilon_{ee})| \ll 1$ , respectively. Note that the terms of  $\mathcal{O}(E^0)$  and  $\mathcal{O}(E^{-1})$  are absent in Eq. (5) which is in perfect agreement with the experimental data.<sup>1</sup> So, taking into account the various constraints described

<sup>1</sup> So far full three flavor analysis of the atmospheric neutrino data with the ansatz (2) has not been performed. In Refs. [6,7,8], the two-flavor analysis of the atmospheric

above, we will work with the ansatz

$$\mathcal{A} = A \begin{pmatrix} 1 + \epsilon_{ee} & 0 & \epsilon_{e\tau} \\ 0 & 0 & 0 \\ \epsilon_{e\tau}^* & 0 & |\epsilon_{e\tau}|^2/(1 + \epsilon_{ee}) \end{pmatrix} \quad (7)$$

in the following discussions. The 90% CL allowed region for the parameters  $\epsilon_{ee}$  and  $|\epsilon_{e\tau}|$  is depicted in Fig. 1. The region  $|\tan \beta| \equiv |\epsilon_{e\tau}|/(1 + \epsilon_{ee})| \gtrsim 1$  is excluded in Fig. 1 because of the atmospheric neutrino data [5].

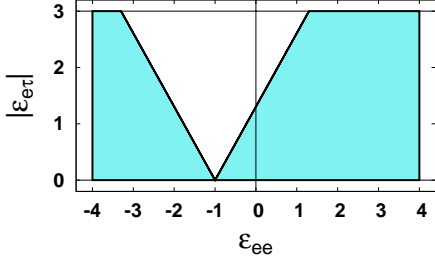


Figure 1. The 90% CL region which is constrained by the current experimental data in the  $(\epsilon_{ee}, |\epsilon_{e\tau}|)$  plane.

The T2KK experiment is a proposal for the future extension of the T2K experiment (see, e.g., references in Ref. [4]). In this proposal, a water Cherenkov detector is placed both in Kamioka (at a baseline length  $L = 295$  km) and in Korea (at  $L = 1050$  km), whereas the power of the beam at J-PARC in Tokai Village is upgraded to 4 MW. To examine whether T2KK can tell the existence of NSI, we introduce the following quantity:

$$\Delta\chi^2 = \min_{\text{param}} \left[ \sum_i \frac{\{N_i(\text{NSI}) - N_i(\text{std})\}^2}{\sigma_i^2} + \Delta\chi_{\text{prior}}^2 \right], \quad (8)$$

neutrino data with the matter effect  $\epsilon_{\alpha\beta}$  ( $\alpha, \beta = \mu, \tau$ ) was performed. In Ref. [9], full three flavor analysis was performed, but it was based on the assumption  $\epsilon_{\alpha\beta}^{eP} = \epsilon_{\alpha\beta}^{uP} = 0$ . In their analysis, therefore, the allowed regions for the parameters  $\epsilon_{\alpha\beta}$  ([8])  $\equiv 3 \sum_P \epsilon_{\alpha\beta}^{dP}$  to be marginalized over are smaller than those in Eq.(3), and the constraint they obtained, e.g., for  $\epsilon_{ee}$  ([8])  $\equiv 3 \sum_P \epsilon_{ee}^{dP}$  is expected to be stronger than that for  $\epsilon_{ee} = \sum_P (\epsilon_{ee}^{eP} + 3\epsilon_{ee}^{uP} + 3\epsilon_{ee}^{dP})$ .

where the prior  $\Delta\chi_{\text{prior}}^2$  is given by

$$\begin{aligned} \Delta\chi_{\text{prior}}^2 &\equiv \frac{(\sin^2 2\theta_{23} - \sin^2 2\theta_{23}^{\text{best}})^2}{(\delta \sin^2 2\theta_{23})^2} \\ &+ \frac{(\sin^2 2\theta_{13} - \sin^2 2\theta_{13}^{\text{best}})^2}{(\delta \sin^2 2\theta_{13})^2} \\ &+ \frac{(|\Delta m_{31}^2| - |\Delta m_{31}^2|_{\text{best}})^2}{(\delta |\Delta m_{31}^2|)^2}. \end{aligned}$$

In Eq. (8) difference of the numbers of events,  $N_i(\text{NSI})$  and  $N_i(\text{std})$  with or without NSI, is compared with the error  $\sigma_i$  for each bin  $i$ , while  $\Delta\chi^2$  is minimized with respect to the oscillation parameters. If  $\Delta\chi^2$  is larger than, e.g., 4.6 for 2 degrees of freedom, then significance for the existence of NSI at T2KK is more than 90% CL. In Fig.2, the contour of the excluded region in the  $(\epsilon_{ee}, |\epsilon_{e\tau}|)$  plane at 90% CL is plotted for various values of  $\sin^2 2\theta_{13}$ ,  $\delta$  and  $\arg(\epsilon_{e\tau})$ . If the true point  $(\epsilon_{ee}, |\epsilon_{e\tau}|)$  is inside each contour, then T2KK cannot prove the existence of NSI.

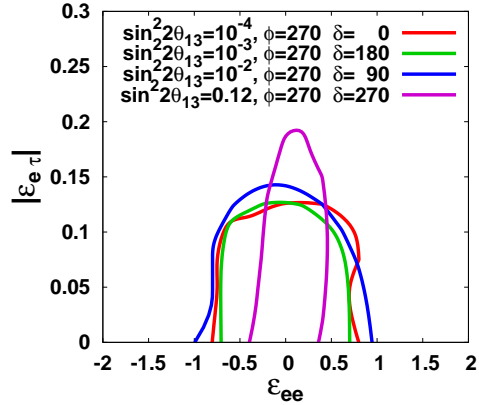


Figure 2. The region which is expected to be constrained by T2KK at 90% CL in the  $(\epsilon_{ee}, |\epsilon_{e\tau}|)$  plane for various values of  $\sin^2 2\theta_{13}$  and for typical values of  $\delta$  and  $\phi \equiv \arg(\epsilon_{e\tau})$  in degrees.

We found from detailed numerical calculations [4] that  $|\epsilon_{ee}| \lesssim 1$ ,  $|\epsilon_{e\tau}| \lesssim 0.2$  will be obtained by the negative results of the T2KK experiment. Thus, the allowed region in the  $(\epsilon_{ee}, |\epsilon_{e\tau}|)$  plane will be updated from Fig.1 to Fig.3 after the T2KK experiment is completed with negative results.

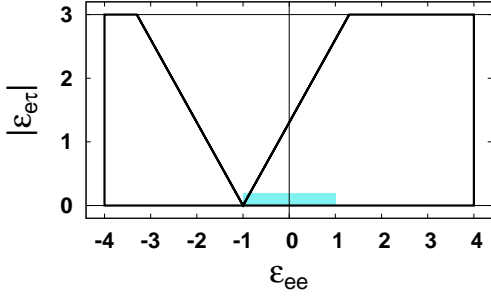


Figure 3. The region which is expected to be constrained by T2KK at 90% CL in the  $(\epsilon_{ee}, |\epsilon_{e\tau}|)$  plane in the case of negative results at T2KK.

On the other hand, if true point  $(\epsilon_{ee}, |\epsilon_{e\tau}|)$  is outside each contour in Fig.2, then T2K should be able to obtain some information on the parameters  $\epsilon_{ee}, |\epsilon_{e\tau}|$ . In this case, it becomes important whether we can also determine the two phases  $\delta$  and  $\arg(\epsilon_{e\tau})$ . The results at 90% CL are shown in Fig. 4 for  $(\epsilon_{ee}, |\epsilon_{e\tau}|) = (0.8, 0.2)$  and  $(2.0, 2.0)$ . As in the standard three-flavor case, if  $\theta_{13}$  is very small, it is difficult to get any information on  $\delta$ . For larger values of  $\theta_{13}$ , the sensitivity to  $\arg(\epsilon_{e\tau})$  depends on the value of  $|\epsilon_{e\tau}|$ . For larger (smaller) values of  $|\epsilon_{e\tau}|$ , sensitivity to  $\arg(\epsilon_{e\tau})$  is good (poor). Qualitative understanding of these features using the analytic form of the oscillation probability  $P(\nu_\mu \rightarrow \nu_e)$  is given in Ref. [4].

In conclusion, we have studied the sensitivity of the T2KK experiment to the non-standard interaction in propagation. If T2KK gets negative results, then we have constraints  $|\epsilon_{ee}| \lesssim 1$  and  $|\epsilon_{e\tau}| \lesssim 0.2$ . If T2KK obtains affirmative results, then T2KK can determine the values of  $\epsilon_{ee}, |\epsilon_{e\tau}|$ , and  $\arg(\epsilon_{e\tau})$ . In particular, if the values of  $\theta_{13}$  and  $|\epsilon_{e\tau}|$  are relatively large ( $\sin^2 2\theta_{13} \gtrsim \mathcal{O}(0.01)$ ,  $|\epsilon_{e\tau}| \gtrsim 0.2$ ), then we can determine the two phases  $\delta, \arg(\epsilon_{e\tau})$  separately.

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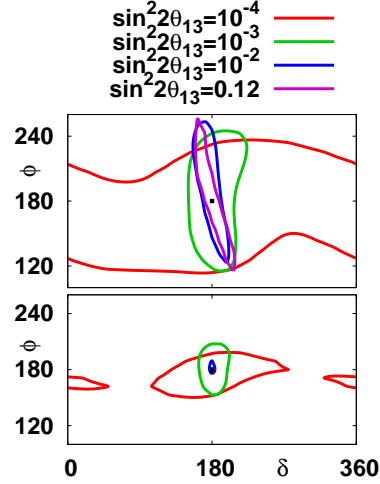


Figure 4. The experimental errors at 90% CL in the measurement of  $\delta$  and  $\phi \equiv \arg(\epsilon_{e\tau})$  at T2KK for  $(\epsilon_{ee}, |\epsilon_{e\tau}|) =$  (a)  $(0.8, 0.2)$ , (b)  $(2.0, 2.0)$  and for various values of  $\sin^2 2\theta_{13}$ . The true values are  $\delta = \arg(\epsilon_{e\tau}) = 180$  degrees.

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